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DEVELOP AND TEST FUEL CELL POWERED
ON-SITE INTEGRATED TOTAL ENERGY SYSTEMS:
PHASE III, FULL-SCALE POWER PLANT DEVELOPMENT

10TH QUARTERLY REPORT: MAY - JULY, 1983

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SECTION I. INTRODUCTION

Engelhard's objective under the present contract is to contribute substantially to the national fuel conservation program by developing a commercially viable and cost-effective phosphoric acid fuel cell powered on-site integrated energy system (OS/IES). The fuel cell offers energy efficiencies in the neighborhood of 40% of the lower heating value of available fuels in the form of electrical energy. By utilizing the thermal energy generated for heating, ventilating, and air-conditioning (HVAC), a fuel cell OS/IES could provide total energy efficiencies in the neighborhood of 80%. Also, the Engelhard fuel cell OS/IES, which is the objective of the present program, offers the important incentive of replacing imported oil with domestically produced fuel.

Engelhard has successfully completed the first two phases of a five-phase program. The next three phases entail an integration of the fuel cell system into a total energy system for multi-family residential and commercial buildings. The mandate of the current Phase III effort is to develop a full-scale 50kW breadboard power plant module and to identify a suitable type of application site. Toward this end, an objective in Phase III is to complete the integration and testing of the 5kW system whose components were developed during Phase II. In addition to the development and testing of this sub-scale system, scale-up activities are to be implemented as a total effort for Phase III. Throughout this design and engineering program, continuing technology development activity will be maintained to assure that the performance, reliability, and cost objectives are attained.

SECTION II. TECHNICAL PROGRESS SUMMARY

TASK I - 5kW POWER SYSTEM DEVELOPMENT

The objective of this task is to complete integration of the 5kW components and sub-systems developed during Phase II.

The 5kW integrated system was returned to testing after completion of control system rework activities in early July. The performance curve obtained for the system is illustrated in Figure 1.

Operation of the system has been generally satisfactory after 24 days in a one-shift-on/two-shifts-off mode. Two electrical/mechanical malfunctions were experienced (a D.C. motor in the reformer-burrer blower and a transistor in the circuit controlling operation of the reactant air delivery blower). Both were quickly remedied through replacement of failed components, and the system was restarted immediately afterward in each case.

TASK II - ON-SITE SYSTEM APPLICATION ANALYSIS

The purpose of this task was to develop an application model for on-site integrated energy systems. The model considers fuel availability, costs, building types and sizes, power distribution requirements (electrical and thermal), waste heat utilization potential, types of ownership of the OS/IES, and grid connection vs. stand-alone operation. The work of this task has been carried out under subcontract by Arthur D. Little, Inc. (ADL), and this work has been completed.

SECTION II. - CONTINUED

The basic structure of the economic analysis has been to compute the internal rate of return to the building owner of various fuel cell-based OS/IES systems versus a conventionally-powered system. The four building types selected are:

- Hospital
- Retail Store
- Apartment Building
- Office Building

These were analyzed over four different electric rate structures representing four combinations of the basic conditions principally affecting charges for electricity:

- High load growth rate
- Low load growth rate
- High oil/gas
- Low oil/gas

Additional variables included in the analysis were climate (Houston, Washington, Chicago), use of centrifugal chillers or absorption chillers for air-conditioning, and the option of thermal storage for thermal-load levelling.

A draft final report on this effort was received from ADL. Results for the various cases were presented using internal rate of return and incremental internal rate of return with increasing fuel cell power system capacity as figures of merit. These and other factors were used in developing an approach for market size estimation.

SECTION II. - CONTINUED

Following a meeting on April 4, 1983 a number of modifications in the draft report were agreed upon concerning the sizes and numbers of buildings attractive as candidates for fuel cell OS/IES, the electricity sell-back assumptions, and the economics surrounding the use of absorption chillers.

The main conclusions of the study are the following:

- (1) The cost of electricity is the most important single factor in determining the attractiveness of a fuel cell system to a building owner.
- (2) The most favorable buildings for fuel cell OS/IES are those with high ratios of thermal load to electrical load.
- (3) Overall, the most attractive market comprises hospitals, apartments and dormitories located in sites where the cost of electricity is relatively high.

Figure 2 qualitatively illustrates the interrelationships among fuel cell costs, electricity costs, building load ratios, and market penetration.

Table I shows the annual energy consumption for various representative sites considered in the study. Figure 3 illustrates the rationale for selecting various candidate sites in the continental U.S., and Table II shows how many new buildings per year would have positive rates of return on OS/IES installations, broken down by building type.

SECTION II. - CONTINUED

TASK III - ON-SITE SYSTEM DEVELOPMENT

This task forms the core of the Phase III contract effort. Work under this task will result in the breadboard design of a system for an on-site application. The power plant will be designed for a rated output of 50kW (electrical) or some multiple thereof. The fuel processor and power conditioner will each be 50kW units, while the 50kW fuel cell will comprise two 25kW stacks. This task is accordingly broken down into four sub-tasks as follows:

- 3.1 Large Stack Development
- 3.2 Large Fuel Processor Development
- 3.3 Overall System Analysis
- 3.4 Overall System Design and Development

A large part of Sub-Task 3.3 was carried out by Physical Sciences Inc. (PSI) under subcontract.

A. LARGE STACK DEVELOPMENT

The 24-cell, two-ft² stack was kept on hot-standby (250-275°F, idle) with intermittent excursions to 375°F on load. The primary objective was to accumulate additional operating hours with the non-metallic cooling plates. These continued to operate satisfactorily during the period with a cumulative operating time of over four months. Cell temperature profiles were determined with the coolant pressure reduced from about 14 psig (1 kg/cm²) to about 9 psig (0.6 kg/cm²). The maximum in-plane ΔT was 9°F (5°C); the maximum centerline ΔT among the cells was about 8°F (4°C); and the ΔT between the coolant inlets and outlets was 13°F (7°C). These ΔT 's are entirely acceptable. (The test results are shown in Figure 4.)

SECTION II. - CONTINUED

Construction activity for the 25kW stack is currently in abeyance. This activity will be resumed under 1984 funding.

B. LARGE FUEL PROCESSOR DEVELOPMENT

Test activity for the 50kW fuel processing sub-system is currently in abeyance. This activity will be resumed under 1984 funding in conjunction with the 25kW stack test program.

C. OVERALL SYSTEM ANALYSIS

The Physical Sciences Inc. subcontract has been completed. Final reports involving the off-design and transient analysis portions of the work have been received. The corresponding computer modules have been integrated into the overall fuel cell system program, and these have been successfully utilized in-house.

D. OVERALL SYSTEM DESIGN AND DEVELOPMENT

The Trane Co. has completed work under its subcontract to Engelhard. The main conclusions of Trane's study with respect to the HVAC sub-system and the utilization of waste heat are as follows:

(1) In the hospital case, the most economical HVAC design should include both a centrifugal chiller and a two-stage absorption chiller, as well as separate provisions for hot storage. The optimum fuel cell capacity would be about 80% of the average electric load of the hospital, and all of the waste heat produced above 180°F (355K) could be utilized. For this case, the differential HVAC system cost for a 460kW on-site fuel cell is estimated to be about \$165,000 greater than the cost of the equivalent conventional HVAC system. This amounts to

SECTION II. - CONTINUED

about \$360 per kW over and above the estimated cost of the basic fuel cell power system. The details are shown in Table III. The effect of this incremental cost on the economics for a selected case is shown in Table IV.

(2) In the apartment case, only a centrifugal chiller (no absorption chiller) and hot storage are called for in the most economical design. Here, the optimum fuel cell capacity is about equal to the average electrical load of the building, and some electricity is sold back to the utility.

(3) In the case of the retail store, the most economical design once again calls for a centrifugal chiller, hot storage, and no absorption chiller. The optimum fuel cell capacity is about 35% of the average electrical load.

(4) For the case of the office building, a centrifugal chiller, hot storage, and no absorption chiller are once again called for. The optimum fuel cell capacity would be about 20% of the average electrical load.

(5) In all cases, a substantial fraction of the waste heat produced above 180°F (355K) would be utilized for hot water or space heating.

(6) A two-stage absorption chiller, the most efficient type of absorption chiller, needs a thermal input higher than about 325°F (436K), a requirement that meshes well with the use of a liquid coolant.

(7) The economic feasibility of the system requires that back-up and supplementary electricity continue to be available as currently mandated by PURPA.

SECTION II. - CONTINUED

Figure 5 depicts schematically the general form of the combined fuel cell and HVAC system. Figure 6 shows the interrelationship between the building load ratio and the fuel cell system size optimized for maximum net present value to the owner. It is seen that the relative economic impact of an optimally-sized fuel cell is far greater in apartments and hospitals than in retail stores and office buildings.

TASK IV - STACK SUPPORT

The purpose of this task, which will continue throughout the contract, is to investigate new materials and component concepts by experimentation and the use of small-stack trials. The criteria for choosing activities under this task are the prospects for improved performance, reduced costs, or improved reliability. Improvements in and performance of electrocatalysts, though generated under Engelhard-sponsored Task VI, will be reported under Task IV.

A. PERFORMANCE OPTIMIZATIONCATALYSTS

Evaluation of the latest developmental cathode catalyst type (E-7) is continuing. (This catalyst is a bimetallic type with nominally 10% Pt on carbon black.) The initial single-cell tests were conducted up to 1700 hours. Initial performance was generally high, but variable (0.725-0.740 V, IR-free, @ 161 mA/cm² and 191°C, H₂-air); and stability was also quite variable, as indicated in Figures 7 and 8.

New E-7 catalyst formulations have been prepared to further examine the stability as well as the repeatability of this catalyst type. Single-cell testing has begun. After 50 hours of operation, an E-7 catalyst is exhibiting 0.731V, IR-free (161 mA/cm², 191°C, H₂-air). Further results will be reported next month.

SECTION II. - CONTINUED

New diagnostic test procedures are being employed to aid in the development and evaluation of advanced anode catalysts. The primary objective for these catalysts is improved tolerance to carbon monoxide.

Table V shows the results of cyclic-voltammetric testing in the presence of N_2 and 5% CO in N_2 . The fraction of electrochemical surface-area retained after exposure to the CO-containing gas is interpreted as an indicator of CO-tolerance. These results suggest that the developmental anode catalyst has potential superiority over the baseline catalyst. Single-cell testing will be pursued.

B. COST REDUCTIONBIPOLAR PLATES

During the reporting period the bipolar plate grooving machine was relocated from rental space to the Union Fuel Cell Facility. Installation has been completed, including hook-up of the water-spray system. Processing trials have begun.

C. RELIABILITYNON-METALLIC COOLING PLATES

Activity during this quarter included assessment of the reliability of a design modification directed toward cost reduction in the non-metallic cooling plate. The details are presented in the Appendix.

SECTION II. - CONTINUED

CARBON PAPER SUBSTRATE WETPROOFING

The effort to optimize fluorocarbon treatment techniques for carbon paper substrates was continued during this reporting period. (See February-April 1983 Quarterly Report.) Bench test results indicated that admixing TFE-30 dispersion with FEP-120 dispersion provides improved shear strength while sustaining low acid uptake. Macroporosity, as reflected by flow rate versus pressure drop tests, is somewhat insensitive to the level of TFE-30 admixing.

Single-cell tests were conducted during June and July to evaluate the effect on performance of substrates treated with these admixtures. The TFE/FEP concentration ratio ranged from 1.6 to 2.8 by weight. The single-cell test results indicate that over this concentration range the reactant diffusion characteristics in the substrate are adversely affected (anode and cathode). Further testing will focus on lower TFE admixing concentrations.

TASK V - FUEL PROCESSING SUPPORT

The intent of this task is to provide background data and information to support the design and construction of an optimized 50kW fuel processor under Task III. Most of the effort of this task was devoted to screening and longevity testing of catalysts for methanol/steam reforming. This task is now complete.

TASK VI - IMPROVED ELECTROCATALYSTS

Developmental electrocatalyst formulations are being prepared under Engelhard sponsorship. These are provided to the main program, and results are reported under Task IV.

SECTION II. - CONTINUED

Development work is being pursued on both cathode and anode catalysts (see Task IV); however, the major activity at the present time is directed toward improved cathode activity.

SECTION III. CURRENT PROBLEMS

NONE.

SECTION IV. WORK PLANNED**TASK I - 5kW POWER SYSTEM DEVELOPMENT**

- Continue 5kW integrated system testing.

TASK II - ON-SITE SYSTEM APPLICATION ANALYSIS

- Finalize Arthur D. Little subcontract report.

TASK III - ON-SITE SYSTEM DEVELOPMENT

- Continue evaluation of non-metallic cooling plates in 24-cell, two-ft² stack.

TASK IV - STACK SUPPORT

- Continue evaluations of E-7 cathode catalyst.

TABLE IANNUAL ENERGY CONSUMPTION FOR
REPRESENTATIVE BUILDING SITES (kWh)

<u>Building</u>	<u>Electricity</u>		<u>Cooling ***</u>	<u>Heating</u>	<u>Hot Water</u>	<u>Total</u>
	<u>HVAC **</u>	<u>Other</u>				
Apartment	354,324	1,015,886	693,657	662,748	732,695	3,459,580
Store	574,693	1,996,185	1,593,694	381,090	127,413	4,673,075
Hospital	1,319,566	3,065,270	3,391,485	1,610,104	4,010,821	13,397,246
Office (Washington)	481,506	615,664	874,655	*	524,199	2,296,024
Office (Chicago)	296,096	829,006	819,150	*	733,117	2,650,369
Office (Houston)	327,405	1,061,785	1,023,152	*	293,705	2,706,047

* Heating load included in hot water load.

** Electricity component that provides the cooling for the building.

*** Actual cooling load.

TABLE IINEW BUILDINGS WITH POSITIVE RATES OF RETURN
FROM A FUEL CELL OS/IES INVESTMENT

	<u>Total New U.S. Field-Engineered Buildings in Average Year</u>	<u>Percent of Buildings In Regions With Positive Rates of Return</u>	<u>New Buildings With Positive Rates of Return</u>
Retail	1000	40	400
Health & Hospitals	450	80	360
Office	2150	40	860
Apartments	200	40	80
Other	<u>1800</u>	<u>40</u>	<u>720</u>
Total	5600	43	2420

Source: Arthur D. Little, Inc., estimates

TABLE IIIINCREMENTAL HVAC SYSTEM COST FOR FUEL CELL INSTALLATION

CHILLED WATER SYSTEM COST		\$ 6,200
a. Chiller Cost Difference	\$ 5,000	
b. Chiller Bypass (one chiller)	\$ 700	
c. Controls	\$ 500	
BUILDING HEATING SYSTEM		\$(12,100)
a. Boiler Cost Difference	\$(21,000)	
b. Water Storage Tank	\$ 3,600	
c. Tank Bypass & 3-Way Valve	\$ 700	
d. Recovery Loop (includes pump, valves, piping)	\$ 3,400	
e. Controls	\$ 1,200	
DOMESTIC WATER HEATING SYSTEM		\$ 6,400
a. Storage Tank	\$ 2,400	
b. Steam/Water HX	\$ 1,300	
c. Tank Heater	\$ (1,400)	
d. Recovery Loop (includes pump, valves, piping)	\$ 3,400	
e. Controls	\$ 700	
HEAT TRANSFER FLUID SYSTEM		\$ 62,000
a. Heat Exchangers HX-1,2,3	\$ 8,000	
b. Pumps P-1 through P-6	\$ 25,000	
c. Cooling Tower CT-2 and Sump	\$ 5,200	
d. Piping, Valves, Expansion Tanks	\$ 18,500	
e. Controls	\$ 5,900	
ELECTRIC COSTS		\$ 70,700
a. Motor Connections	\$ 7,700	
b. Paralleling Gear	\$ 98,000	
c. No Emergency Generator	\$(35,000)	
MISCELLANEOUS COSTS		\$ 31,500
a. Additional Mechanical Space (\$30/sq.ft.)	\$ 30,000	
b. Exhaust Stack, Inlet Duct, Natural Gas Pipe for Fuel Cell	\$ 1,500	
TOTAL ADDITIONAL COST		<u>\$164,700</u>

() Denotes a credit

TABLE IV
EFFECT OF INSTALLED COST ON
ECONOMICS OF ON-SITE FUEL CELL

HOSPITAL, WASHINGTON, D.C.

460kW FUEL CELL SYSTEM WITH CENTRIFUGAL AND
TWO-STAGE ABSORPTION CHILLERS AND HOT STORAGE
CON EDISON RATES

1. INSTALLED COST	
HVAC OVER CONVENTIONAL	\$164,700
FUEL CELL @ \$980/kW	450,800
TOTAL	615,500
2. ECONOMICS	
NET PRESENT VALUE	\$615,500 *
INTERNAL RATE OF RETURN	33.0% **

* Sum of net operating cost savings over life cycle less incremental initial and replacement costs. (Based on 48% income tax rate; all costs and cost savings discounted at 15% per year.)

** Annual rate at which costs and cost savings must be discounted in order to obtain a net present value equal to zero.

TABLE V
EFFECT OF CARBON MONOXIDE ON
ELECTROCHEMICAL Pt SURFACE-AREA OF ANODES

<u>Catalyst</u>	<u>Anode</u>	<u>Description</u>	<u>Pt Surface-Area *</u> <u>(m²/g Pt)</u>	
			<u>N₂</u>	<u>5% CO/N₂</u>
A-1	2121	Baseline Type	109	78
A-1	2154	Baseline Type	129	100
A-2	2354	Developmental Type	138	132
A-2	2355	Developmental Type	136	129

* Measured by cyclic-voltammetry. Samples were in 25% H₃PO₄ at 25°C, saturated with N₂ and 5% CO/N₂, respectively.

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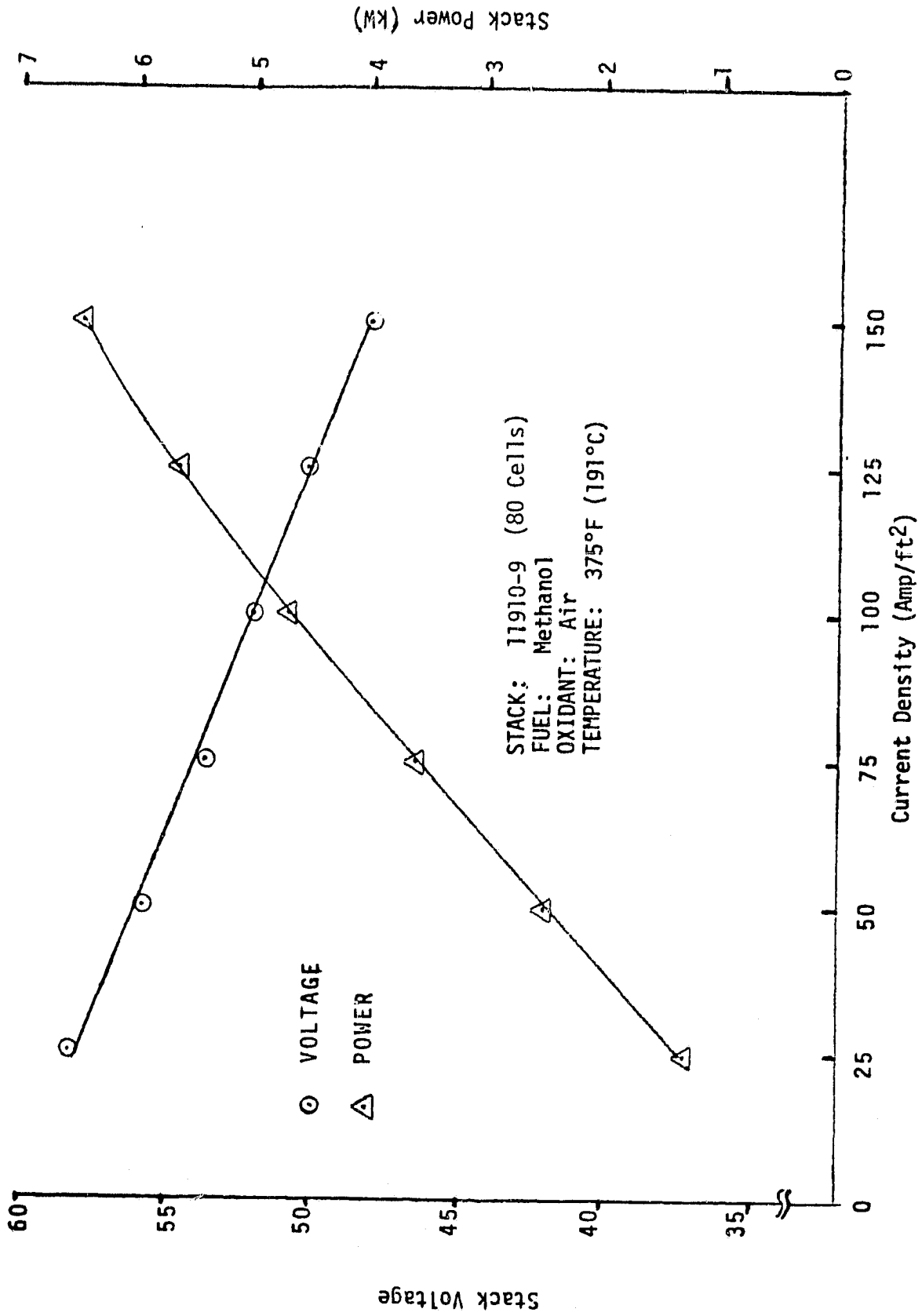


FIGURE 1 PERFORMANCE OF 5kW INTEGRATED SYSTEM

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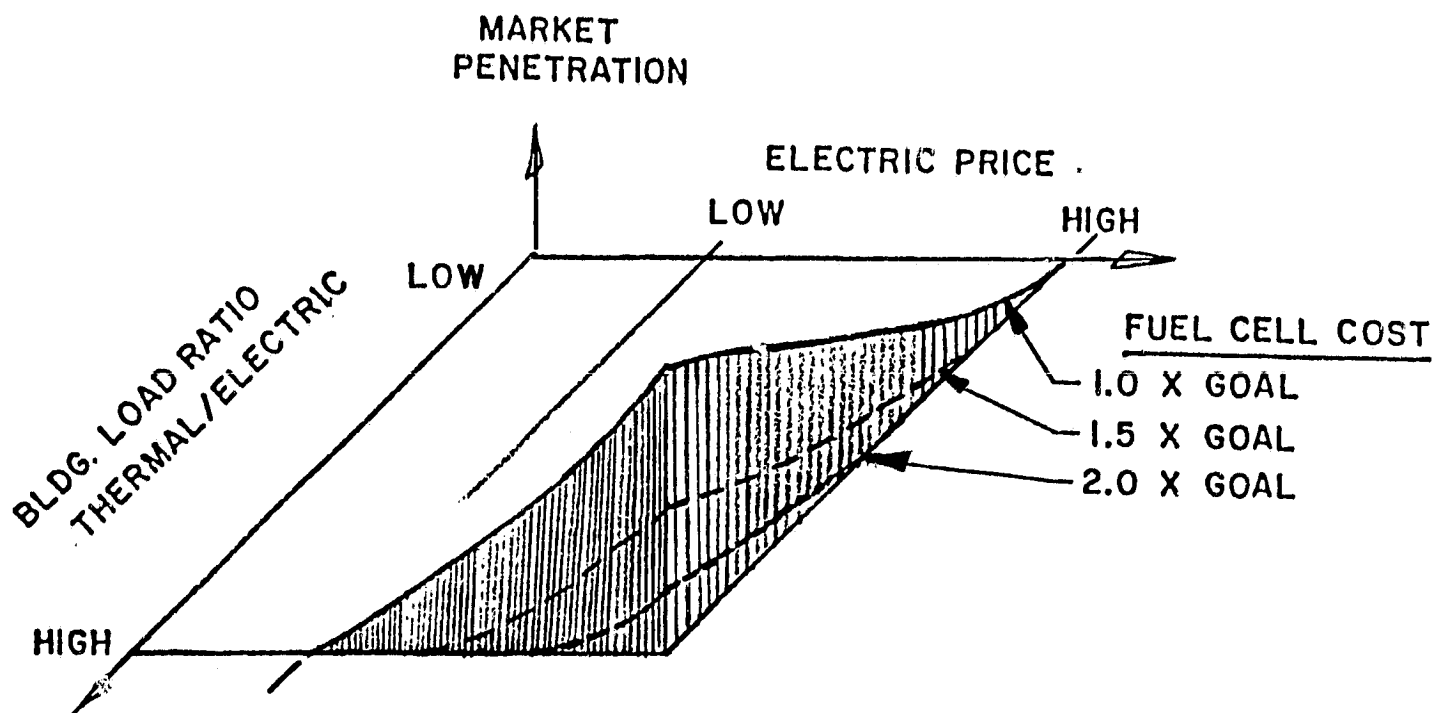


FIGURE 2 MARKET PENETRATION RELATIONSHIPS

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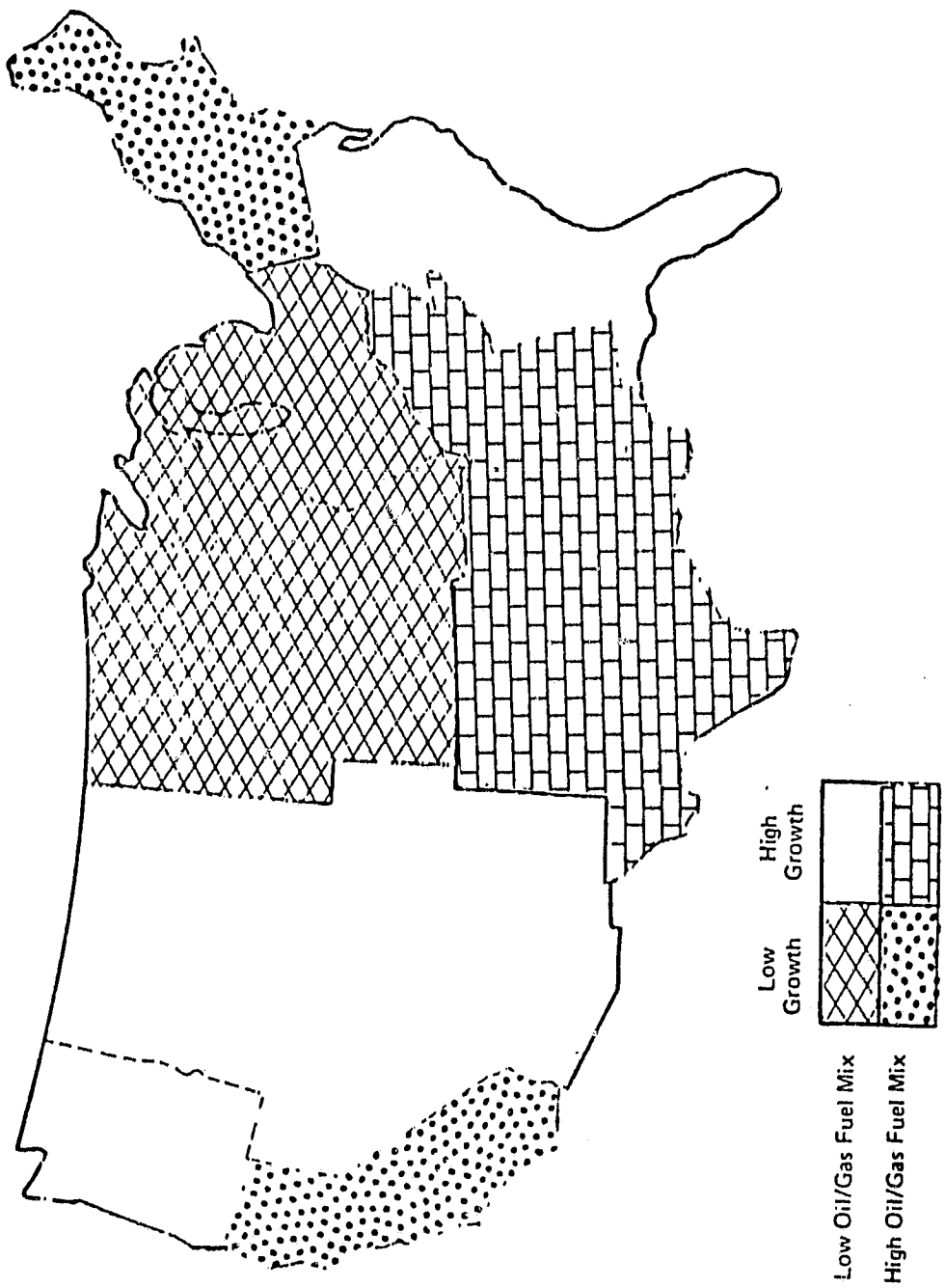


FIGURE 3 OS/IES STUDY REGIONS

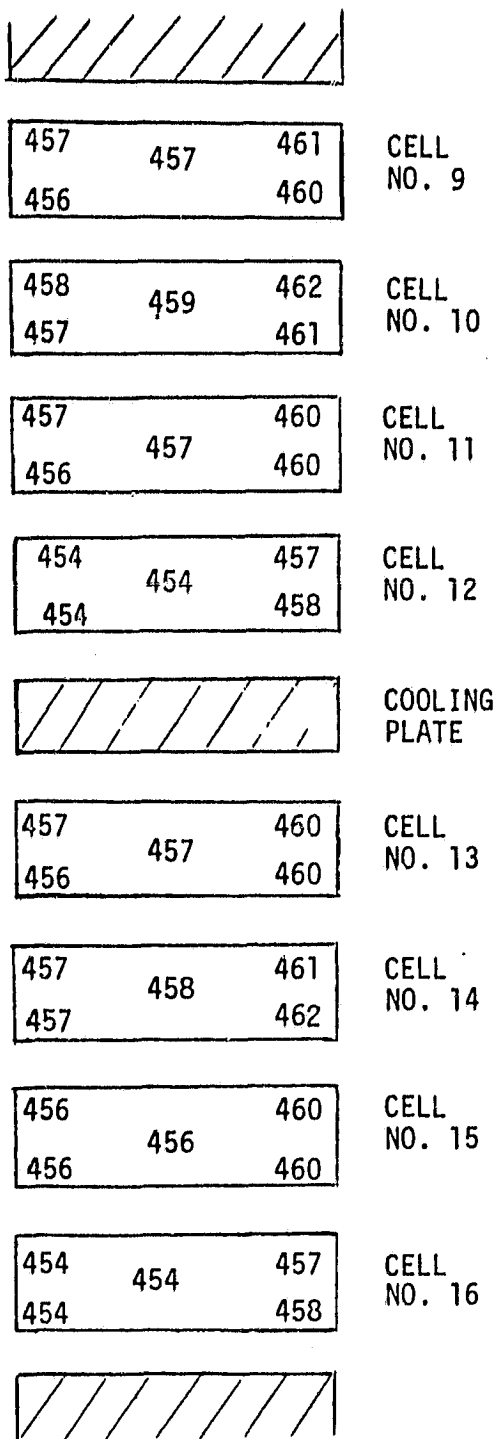


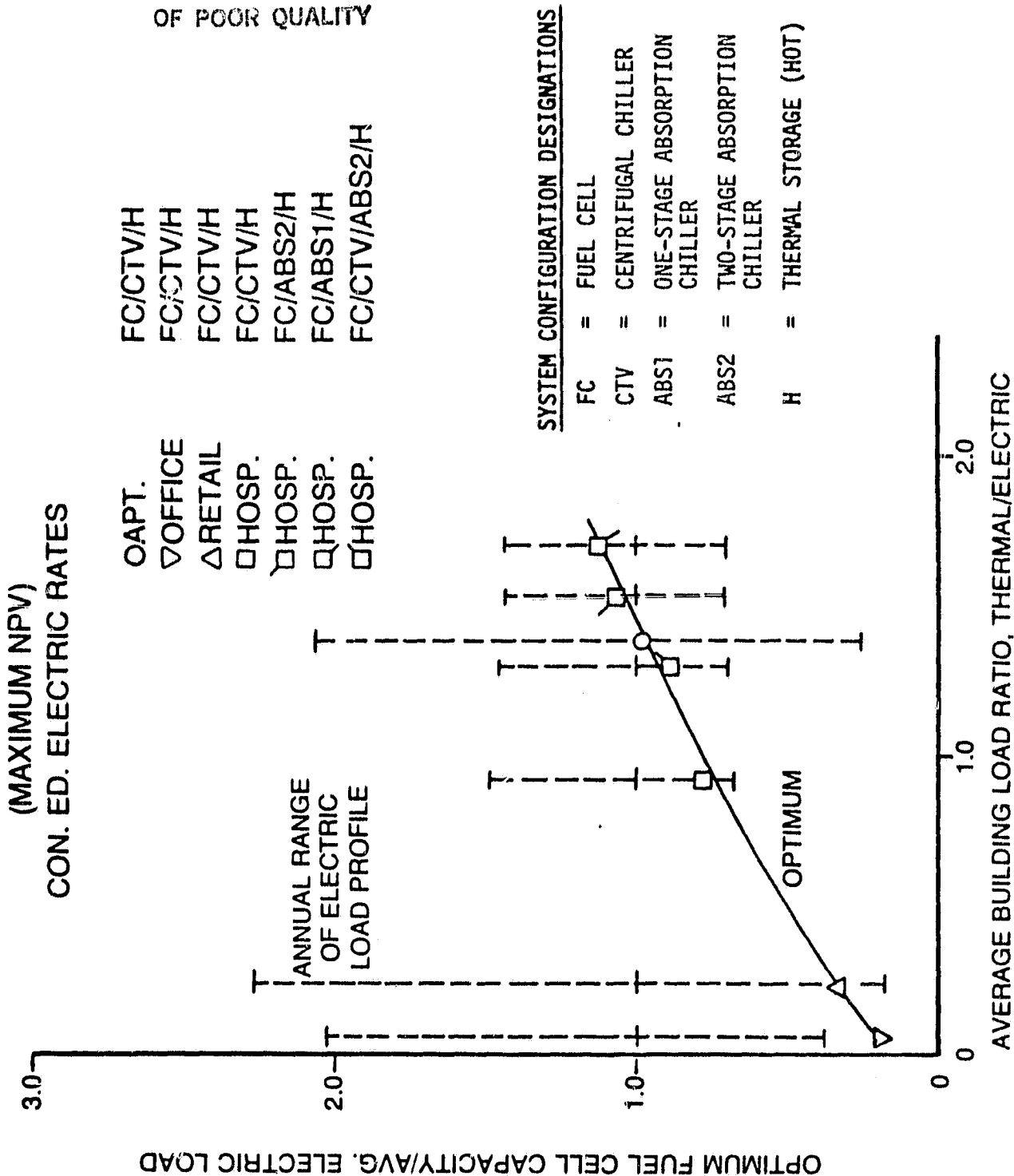
FIGURE 4

CELL TEMPERATURE UNIFORMITY IN
24-CELL, TWO-FT² STACK USING
NON-METALLIC COOLING PLATES

- 150 ASF (161 mA/cm²)
- 2.5 X STOICH. AIR
- TEMP. IN K
- COOLANT INLET: 443K
- COOLANT OUTLET: 450K
- $\Delta P = 9$ PSI (0.6 kg/cm²)

FIGURE 6

OPTIMUM FUEL CELL CAPACITY



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VOLTAGE,
IR-FREE
(mv)

800

700

600

CHARGES, 1000: 15
OF POOR QUALITY

RUN: 1114

CATHODE: 2376 (11768-6-2)

ANODE: 2328 (11760-31-1)

TEMP.: 375°F (191°C)

CURRENT DENSITY: 150 Amp/Ft² (161 mA/cm²)

△ = H₂/Air



FIGURE 7

PERFORMANCE STABILITY OF SINGLE-CELL, UTILIZING E-7 CATHODE CATALYST

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RUN: 1118

CATHODE: 2376 (11768-6-2)

ANODE: 2295 (11588-49)

TEMP.: 375°F (191°C)

CURRENT DENSITY: 150 A/ft² (161 mA/cm²)

○ = H₂/O₂

△ = H₂/Air

VOLTAGE,
IR-FREE
(mv)

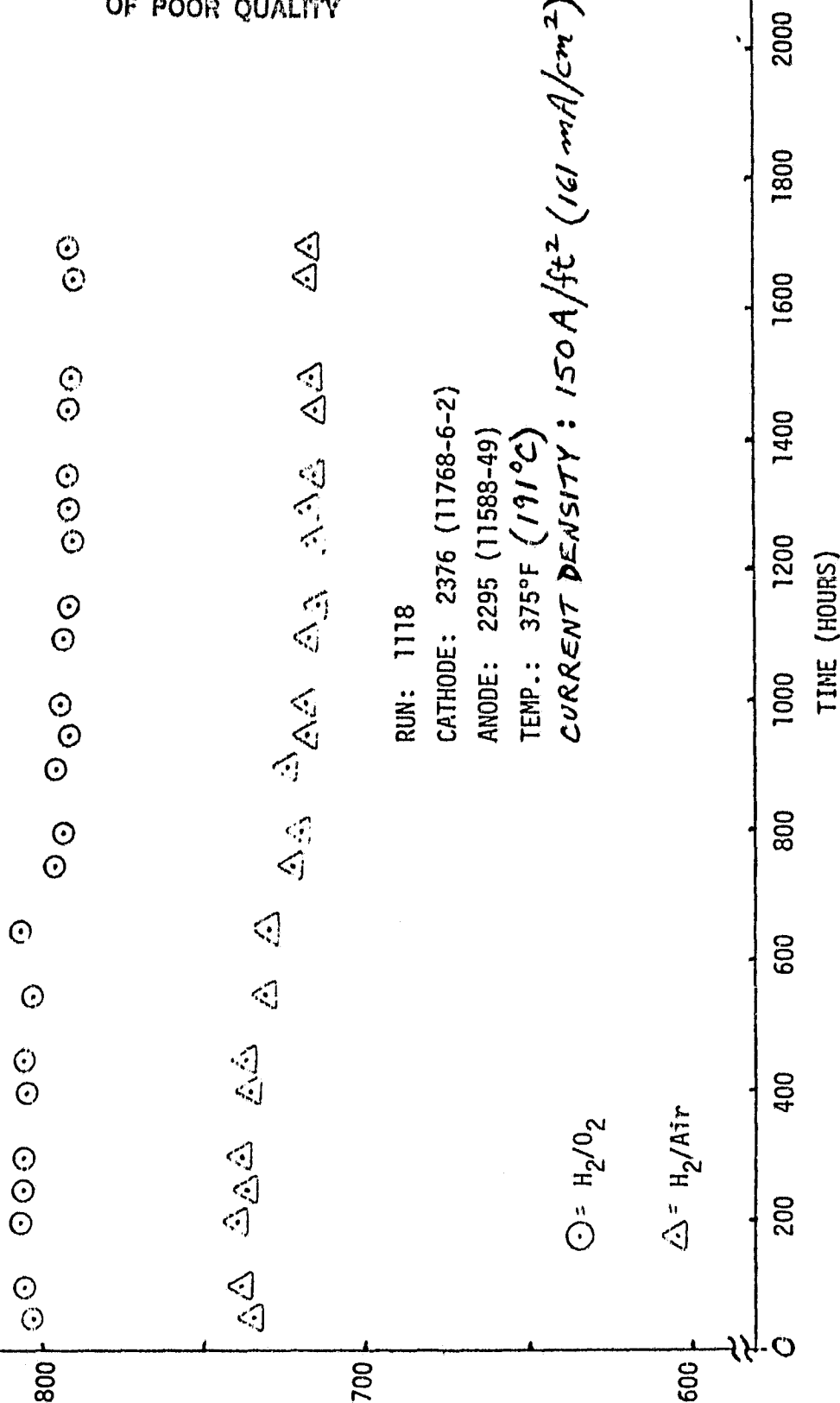


FIGURE 8 PERFORMANCE STABILITY OF SINGLE-CELL UTILIZING E-7 CATHODE CATALYST